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Development of a Biologically Inspired Hopping Robot –"Kenken"

S.H.Hyon, T.Mita

Abstract— **As many biomechanists indicate, tendon plays important role for running or jumping motion. It stores the kinetic energy as a potential energy during stance and also absorbs the impulse at touch down. Inspired by such biomechanical studies, we propose a new simple mechanical model for hindlimb of a dog to realize a robot that imitates dog running, and the hardware design of one-legged running robot, "Kenken". The robot has an articulated leg and uses two hydraulic actuators as muscles and a tensile spring as a tendon. The spring being attached like gastrocnemius or plantaris enables the robot to produce sufficient propulsion force by virtue of the "energy transfer" from the knee, even if there is no actuator at the ankle joint. Using an empirical controller based on the characteristic dynamics of the model, the robot has succeeded in planar one-legged hopping. Although the problem related to the stability at the higer speed remains, the experimental results demonstrate that the proposed hindlimb mechanism is effective for legged running.**

Keywords— **Hopping robot, Running robot, Legged locomotion, Biomechanics, Tendon.**

I. INTRODUCTION

Matsuoka may be the first researcher in running robot. He analyzed a linearlized two-link model with mass-less leg, and proved the foot placement(and its velocity) is essential for the gait stability, and realized stable hopping motion in an inclined gravity field [1].

In a gravity field, animals must bear about more than two-times larger ground force than their weight. Moreover, they suffer from large impulse at touch down. As many biomechanists indicate, tendon plays an important role for running or jumping motion. It stores the kinetic energy as a potential energy during stance and also absorbs the impulse at touch down.

To realize a running robot, introducing such springy characteristics into the leg design is quite natural. The pioneering work was done by Raibert and co-workers. They developed one-legged, biped, and quadruped running robots, all of of them have springy legs of telescopic type, and realized various running motions [2]. They also succeeded in acrobatic motions [3][4]. Buehler and his co-workers have developed an electrically driven one-legged robot, which has spring at the hip joint [5], and realized an energy-efficient running using modified Raibert's controller [6].

Since Raibert's controller is based on the uncontrolled dynamics of the springy leg, it does not require much control effort and yields quite natural running gait. To embed the uncontrolled dynamics into the control algorithm, Raibert made an assumption of decoupling of the rotary motion of the body from the telescopic motion of the leg. Therefore, for his controller applicable to one-legged hopping, the mechanical model itself should be carefully designed to satisfy the assumption: the leg should be sufficiently light compared to the body and the C.M. (center of mass) of the body should be positioned closely to the hip joint. For example, a novel design can be found in Zeglin's "Bow Leg Hopper" [8], where the leg dynamics is "mechanically" decoupled from the body dynamics during stance and the body attitude is passively stabilized because the C.M. of the body is below the hip joint.

Animals leg in the nature, however, is an articulated-type and the C.M. of the body is set off the hip joint. As their dynamics have a strong nonlinear coupling, analysis of uncontrolled dynamics is very difficult and there are few theoretical studies [7]. Moreover, to the best of our knowledge, there have been no successful experiments in running of this type of robots, except for two examples: "Monopod" [9] and "Uniroo" [10], studied by Raibert and his co-workers in 90's. In order to realize robotic running as animals do, it goes without saying that we should establish general control theory for running. Nevertheless, we think it is also important to invent several new mechanical models, inspired by biological or biomechanical studies, as the examples above, and to demonstrate successful experimental results.

In this paper, as our first step toward the goal of dynamic quadruped running, we propose a new simple mechanical model of hindlimb and the hardware design of a one-legged hopping robot named "Kenken". This robot has an articulated leg composed of three links and uses two hydraulic actuators as muscles and linear springs as a tendon. Using an empirical con-

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troller based on characteristic dynamics of the model, the robot has succeeded in hopping in a plane.

This paper is organized as follows. A new mechanical model of hindlimb is proposed in Section II, design and hardware overview of the hopping robot–"Kenken" is described in Section III. Details of the controller are shown in Section IV. Experimental results and discussion are given in Section V.

II. Proposal of a new mechanical model of hindlimb

A. *Role of tendon, articulated leg*

Alexander modeled a muscle and tendon system of leg as a serial connection of inelastic actuator and a spring , and studied the role of tendon during running. He described in [11], there exists unique running speed where the length of muscle is maintained constant, and the mechanical energy is preserved. In this case, the mechanical work for running is not done by the muscle, but by the elastic tendon [12]. Achilles tendon, in particular, is known to have large elasticity and ability to store up to 35% of mechanical energy in human or kangaroo running [13].

In design of a robot capable of running which needs more energy than walking, it is not a clever idea to assign the mechanical work to the actuators only. Instead, it is quite effective to use energy storing mechanism like spring. If we intend to do so, the most direct and simple implementation will be the linear mass–spring model adopted in the Raibert's robots [2]. For studying the mechanism of animal running, this model is very tractable, and many biomechanics researcher dealt with this model. For example, McMahon uses this model to discuss relationship between running speed and the spring constant in real animal [14][15].

However, there certainly are some reasons that real animals adopt not such a telescopic leg, but articulated one and we summarized the practical advantages of articulated-type leg below.

(1) Large reachablity range → more clearance between foot and ground.
(2) Passive leg retraction during flight (provided if the link parameters are appropriately chosen).
(3) Simple structure, because it connects two ends of links with rotary joint → easy to build.

In particular, (2) is helpful for energy-efficient running and has already seen in passive walking robot [16]. Therefore, we are interested in an articulated leg for running robot, not only from its reality, but also from its utility.

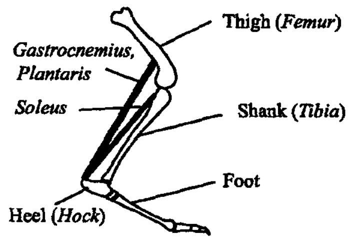


Fig. 1. Muscle group of ankle joint

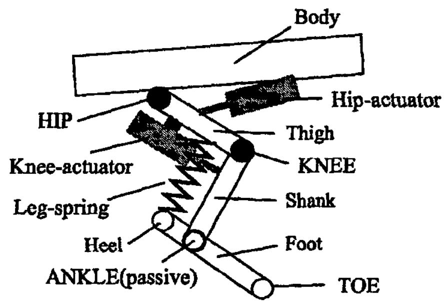


Fig. 2. One-legged robot with new hindlimb mechanism

B. *New simple hindlimb mechanism*

There are several design solutions to make an articulated leg springy. Arranging the mechanism of serial connection of inelastic actuator and a spring to each joint is one possibility. By using this design, Pratt realized natural walking of a biped robot [17]. However, how to link "multiple" passive joints with meaningful periodic running motion is so difficult problem that there is no successful examples so far.

Instead of considering multiple passive joints, here we forcus on only one tendon; the ankle tendon. **Fig.1** shows extensors of an ankle joint. We aimed at the arrangement of the muscle groups, named "gastrocnemius" and "plantaris", and proposed new leg model shown in **Fig.2**, in which the leg spring is attached to the same position as those muscle groups.

It is a planar one-legged robot that has articulated leg composed of three links. It has two active joints, hip and knee, and one passive joint, ankle, and there is no actuator at foot (this means the toe can rotate on the ground during stance phase, acting like a free pivot).

The most distinctive feature of this model is the arrangement of the leg spring. The leg spring is attached between thigh and heel parallel to the shank. The arrangement of the leg spring in this way yields the following two important effects during hopping:

- During stance, holding the knee joint enables the

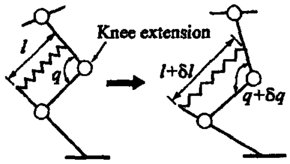


Fig. 3. Active energy pumping mechanism

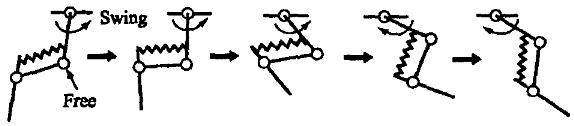


Fig. 4. Passive leg retraction

leg spring to absorb large impulse at touch-down and to transfer its kinetic energy to potential energy for the next stride. Extending the knee yields an extra displacement of the spring, and hence it adds potential energy to the spring (**Fig.3**).

- During flight, the spring constitutes a member of "parallel four-bar linkage", because compressive force to the spring is not so large at that duration. Consequently it enables passive retraction and extension of the leg, provided if the inertia of the links are chosen appropriately (**Fig.4**).

Prilutsky and Herzog show by experiments with cat that there is a transfer of energy between the ankle and knee joints via gastrocnemius and plantaris, and conclude this serves for energy-efficient running motion [18][19]. Using this model, we can see how the ankle tendon operates on the run, in combination with the proximal joint motions. On the other hand, the spring arrangement in "Uniroo" [10] is the same as "soleus" in **Fig.1**.

Fig.5 illustrates one stride of hopping motion, together with each instant of phase transition (touch-down, bottom, lift-off, apex).

III. One-legged hopping robot –"Kenken"

Fig.6 shows "Kenken", the one-legged hopping robot which was designed and built based on the leg model proposed in the previous section. Main specifications are given in **Table I**.

We relied on some articles related to biomechanics to choose the link parameters. A medium-sized dog about 0.5[m] in hip height was selected as a target model. Length of all links (including foot) was chosen to be the same 0.18[m], for tractability of kinematics. This corresponds to the range of the leg length from 0.31[m] to 0.54[m] for ideal parallel four bar linkage. The mass of the leg is relatively large, 3.6[kg]. Individual mass of thigh, shank, and foot is 2.42[kg], 0.75[kg],

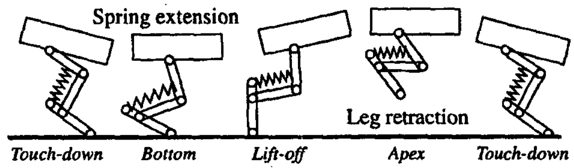


Fig. 5. Leg operation during one stride of hopping

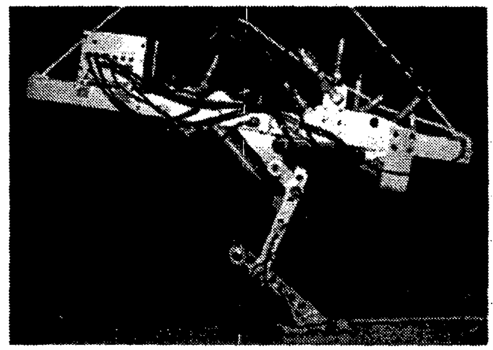


Fig. 6. One-legged hopping robot –"Kenken"

0.43[kg], respectively. The C.M. offset from the hip joint is about 0.10[m]. For the leg spring, two tensile coil springs are installed in parallel between thigh and heel. Initial value of the spring constant was determined by a simple energy analysis.

Since running requires relatively high energy and always accompanies the shock against the ground, the joint actuation is the most critical problem in hardware realization. We introduced a powerful hydraulics and developed a small and lightweight servo actuator, directly mounted with an industry servo-valve. In this

TABLE I
Main specifications of "Kenken"

Parameter	Unit	Value
total mass	kg	13.26
body mass (incl. boom)	kg	9.66 (0.5)
leg mass	kg	3.60
body length	m	0.85
thigh, shank, foot length	m	0.18
toe length	m	0.05
leg length (max.)	m	0.52
leg length (min.)	m	0.31
maximum stride	m	0.52
body inertia around hip	kgm^2	0.46
leg inertia around hip (max.)	kgm^2	0.13
leg inertia around hip (min.)	kgm^2	0.07
leg spring coefficient (each)	N/m	10000
length of moment arm	m	0.06
rated actuator force @14MPa	N	2200
rated actuator speed @14MPa	m/s	2.21

sence, we gave priority to the stiffness over the autonomy. For the passive leg retraction during flight mentioned in Section II-B, the actuator force must be zero. But this is difficult for a commercial flow-control servo-valve and we have abandoned this at the prototype stage.

The experimental setup is like a Raibert's one. A tether boom constrains the robot to sagital plane and measures the horizontal position, vertical position, and pitch angle of the body via three optical encoders. It also carries hydraulic hose, signal line, and DC line. Aluminum box attached to the rear includes interface circuit, servo amplifier, and signal conditioning circuit, which were hand-made with taking the impulses and vibrations into account. The control program is written in MATLAB/SIMULINK code and runs in a single timer task with sampling period 0.5[ms].

IV. An empirical controller for stable hopping

In order to see the effectiveness of our leg mechanism, we tried to achieve a one-legged hopping of the robot, although it is a challenging task to stabilize it. For this, we designed the controller in the form of "finite state machine (FSM)". That is, we divide one stride of hopping into several discrete states, then describe the transition (switching) law and design the control law for each state. Then, the continuous states of the system transit according to this FSM and we obtain periodic hopping gait. Each of the control laws are derived based on the characteristic dynamics of our model. The values of the control parameters are determined empirically.

The coordinates of the robot are defined in **Fig.7**. The controlled variables are $(\dot{x}, \dot{z}, \phi)$: the forward seed, vertical speed, and attitude of the body in the sagital plane. The "virtual leg" length r and angle θ, which are used in the control at flight, are also defined in the figure. Our control inputs are i_1 and i_2, the input currents to the hip actuator, and the knee actuator respectively (for reason as described below). Clearly this model is under-actuated, as there are only two inputs, while the number of the controlled variables is three.

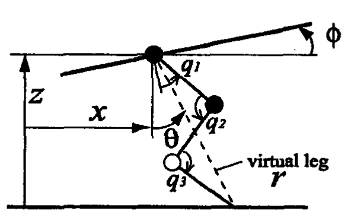


Fig. 7. Coordinates (● denotes actuated joints, ○ denotes passive joint)

This is why we control each variables "intermittently" using FSM.

In this section, after introducing characteristic dynamics of our model in Section IV-A, we propose the control law for the stance phase in Section IV-B, and for the flight phase in Section IV-C. They are combined to the FSM in Section IV-D.

A. Characteristic dynamics of the model

Raibert derived the controller based on the uncontrolled dynamics of simple telescopic type leg [2]. For the mechanical system in general, "uncontrolled" means zero applied force or torque. This is a problem for our robot. A flow-controlled hydraulic servo actuator has less force controllability (we should consider the active joints as very stiff)[4]. That is why we defined the control input as the input currents to the servo amplifier, instead of the actuator force. In this case, zero input implies holding joints with actuators (since hydraulic servo valve has a very high pressure gain, it is easy to hold joints even under a relatively heavy load). Note that holding joints during hopping is allowed because the leg spring absorbs large amount of touch-down impulse.

Hence, we derive the controller based on "characteristic" dynamics of our model, which means, in our case, the dynamics which appears according to the input currents to the actuators. From simulation, we obtained the following basic characteristics:

(a) Dropping with both control inputs zero ($i_1 = 0$, $i_2 = 0$), negative pitching($\dot{\phi} < 0$) occurs at touch-down to the bottom, and after that, it turns to a positive one ($\dot{\phi} > 0$). Then, the robot eventually lift off with positive angular momontum (**Fig.8**).

(b) Control inputs that extends either hip joint or knee joint ($i_1 > 0$ or $i_2 > 0$), produces a spring extension, as well as a positive or negative body pitching (**Fig.9**).

These characteristics come from the C.M. offset from the hip joint and the articulated leg design.

B. Control during stance

Since our robot has only two inputs, two variables can be controlled independently. Based on observation of the characteristic dynamics at stance phase above, we control the attitude and the vertical speed of the body as follows.

$$i_1 = \begin{cases} -K_p(\phi - \phi_d), & \text{if } \phi \le \phi_d \\ 0, & \text{else} \end{cases} \qquad (1)$$

[4]We refer the readers to [20] for the force control using flow-control hydraulic servo valve. We shall also refer to [21], where interesting force controllable actuator, composed of spring and hydraulic actuator in series, is given.

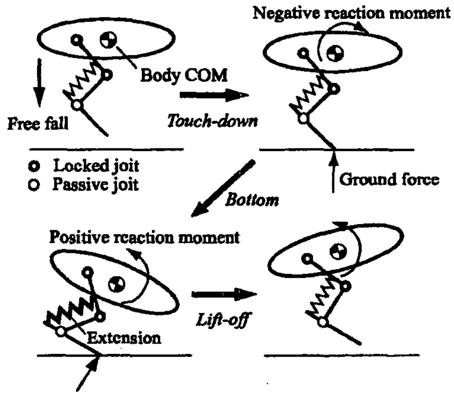


Fig. 8. Free motion

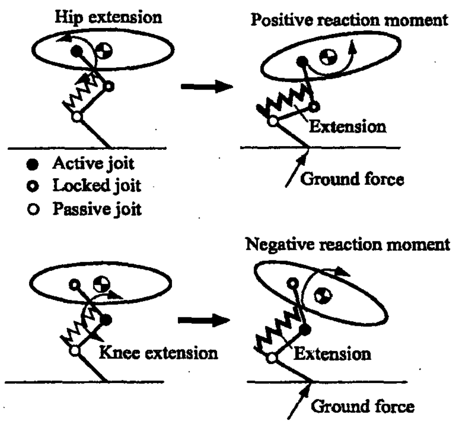


Fig. 9. Actuated motions

$$i_2 = \begin{cases} i_c, & \text{if } \dot{q}_3 \geq 0,\ \dot{z} \leq \dot{z}_d,\ r < r_{max} \\ 0, & \text{else} \end{cases} \quad (2)$$

Where, K_p is a position gain, ϕ_d is a desired attitude, $\dot{z}_d$ is a desired vertical speed, i_c is a constant current, and r_{max} is the maximal virtual leg length.

Eq.(1) and (2) mean that the hip actuator controls body pitch by a feedback law which is executed "only when" the pitch angle is lower than specified value, while the knee actuator controls vertical speed and also suppresses the positive body pitch by giving a constant input, which is exerted "only when" the bottom occurs.

C. *Control during flight*

During flight, the robot swings the leg to prepare for the next touch down. It also retracts and extends the leg to reduce the inertia for fast leg swinging and not to stub against the ground. We note that the touch-down angle (foot placement) of the leg is critical to the gait stability of the robots that cannot change leg length arbitrarily and have no actuator at foot [22][23].

Although our robot has no actuator at foot, it has a knee actuator that can be used to control the leg length. But we have already used the knee actuator for the vertical speed control. Hence, we use the touch-down leg angle for the forward speed control, following Raibert's algorithm [2].

That is, we choose the desired touch down angle θ_f of virtual leg as:

$$\theta_f = \theta^* + K_f(\dot{x} - \dot{x}_d) + \theta_0 \quad (3)$$

where

$$\theta^* = \arcsin\left(\frac{1}{r_0}\frac{\dot{x}T_s}{2}\right) \quad (4)$$

Here, $\dot{x}_d$ is a desired forward speed, and T_s is the stance time which decreases as the forward speed increases [15]. The constant r_0 is the nominal length of the virtual leg, θ_0 is introduced empirically to reduce the coupling effects from the offset of the C.M.. Control parameters are a feedback gain K_f and θ_0.

Having determined the touch-down angle θ_f, the hip actuator swings the leg so that it tracks a smooth reference trajectory $\overline{\theta(t)}$ which reaches θ_f. Also, for leg retraction, we give a smooth reference trajectory $\overline{r(t)}$ which reaches the nominal length r_0. Then, the simple local feedback law can be applied.

$$i_1 = -K_1(q_1 - \overline{q_1}) \quad (5)$$
$$i_2 = -K_2(q_2 - \overline{q_2}) \quad (6)$$

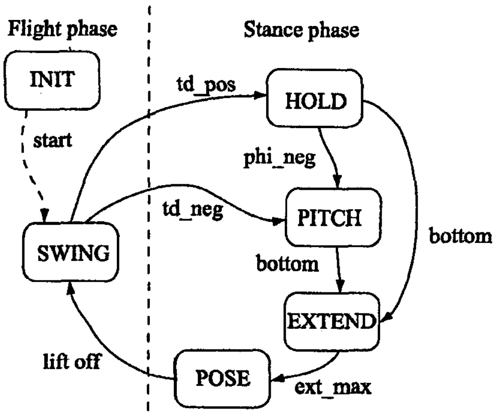
Here, $\overline{q_1} = q_1(\overline{r(t)}, \overline{\theta(t)}), \overline{q_2} = q_2(\overline{r(t)}, \overline{\theta(t)})$ are the desired joint trajectories calculated via inverse kinematics of the parallel four-bar linkage mechanism and K_1, K_2 are the position gains.

D. *Implementation of the controller*

Fig.10 shows the FSM which combines the controllers described in Section IV-B and Section IV-C. Each discrete state and the corresponding control law, as well as the events and the corresponding switching conditions, are summarized in the table, where *sw* represents ON/OFF state of the foot switch. The situation that does not obey these transition rules implies falling down. We used SIMULINK/*Stateflow* for programming the FSM.

V. Experimental results and discussion

Using the controller described in Section IV, the experiments for one-legged hopping were carried out. **Table II** gives a list of initial conditions and control parameters. Since we have not yet applied optimization or learning, the control parameters as well as the



State	Control action
HOLD	$i_1 = 0, \quad i_2 = 0$
PITCH	$i_1 = -K_p(\phi - \phi_d), \quad i_2 = 0$
EXTEND	$i_1 = -K_p(\phi - \phi_d)$, or 0, $\quad i_2 = i_c$
POSE	$i_1 = 0, \quad i_2 = 0$
SWING	$i_1 = -K_1(q_1 - \overline{q_1}), \quad i_2 = -K_2(q_2 - \overline{q_2})$

Event	Condition when event occurs
td_pos	$sw = 1, \quad \phi - \phi_d > 0$
td_neg	$sw = 1, \quad \phi - \phi_d \leq 0$
phi_neg	$\phi - \phi_d \leq 0$
bottom	$\dot{q}_3 \geq 0$
ext_max	$r = r_{max}$, or $\dot{z} - \dot{z}_d > 0$
lift off	$sw = 0$

Fig. 10. Controller implemented as FSM

leg spring stiffness are tuned empirically. The robot is controlled to 2[m/s] vertical speed , -5[deg] pitch angle, and $0 \sim 1.5$[m/s] forward speed at lift off. **Fig.11** $\sim$**Fig.14** depict the corresponding time evolutions. **Fig.15** is the snapshots of a hopping motion. We feel it looks very similar to the motion of dog hindlimb.

In all experiments, the robot is initially set to be 0.1[m] away from the ground, and then dropped. Note that $\dot{x}$ (denoted by xD in the figures) represents the velocity of the hip, not of the C.M.. The dashed line in the graph of r and θ, represents a "dummy" trajectory, i.e. a situation where the angles of ankle and knee are the same ($q_3 = q_2$). The pressure supply for the actuator was set to 7[MPa], half of the rated pressure, because we have a plan to extend this one-legged robot to the biped and quadruped robot(weight becomes larger) in the near future. The experimental results shows that our hindlimb mechanism can produce enough propulsion force for hopping at various speed.

We also tried parameters different from **Table II**,

TABLE II

Parameters in experiments

	Unit	Value		Unit	Value
ϕ_0	deg	-10	K_p	mA/rad	7
θ_0	deg	10	i_c	mA	0.5
r_0	m	0.47	K_f	s/m	0.1
z_0	m	0.55	θ_0	deg	10
ϕ_d	deg	-5	K_1	mA/rad	100
$\dot{z}_d$	m/s	2	K_2	mA/rad	100

	Unit	Fig.10	Fig.11	Fig.12	Fig.13
$\dot{x}_d$	m/s	**0.0**	**0.5**	**1.0**	**1.5**

and obtained the following observations. Stability and tracking performance is better at lower speed (below 1[m/s]) than higher speed. Actually, at faster speed than 1.5[m/s], the speed does not regulate to desired one, as seen from **Fig.14**. This instability at higher speed seems mainly by the deviation of pitch angle at touch-down.

We can see from the plots, that the faster desired speed, the larger leg angle at touch-down because of Eq.(3), which results in more nose-down body pitch angle at touch-down. Because of the control law for the body pitch (Eq.(1)), different body pitch angle at touch-down results in different motion during stance phase, even if the leg angle at touch-down is identical.

There are two ways to avoid such a deviation of the body pitch angle at touch-down. The simplest way will be replacing the leg by more lightweight one. It just reduces the amplitude of the body pitching, relatively to the leg swinging during flight phase. The other way is to actively control the body pitching, by installing an tail mechanism into the body as "Uniroo" [10] does, or introducing some nonholonomic attitude controls [24].

VI. Conclusion

Inspired by biomechanical studies on animal running, we proposed a new simple mechanical model for hindlimb of a dog and developed the one-legged hopping robot, "Kenken". The leg spring being attached like gastrocnemius or plantaris, enables the robot to produce sufficient propulsion force, by virtue of an energy transfer from the knee, even if there is no actuator at the ankle joint.

Using an empirical controller based on characteristic dynamics of the model, the robot has succeeded in planar hopping, although the problem related to the stability at the higher speed remains.

Therefore we conclude that our proposed mechanism is actually suited for the hindlimb of the dog-like robot which we plan to develop. Additionally, we feel it is the first time that such a realistic gaits as shown in Section V, were achieved in a machine (not in a computer simulation). We believe this paper would contribute to both robotics and biomechanics on legged locomotion.

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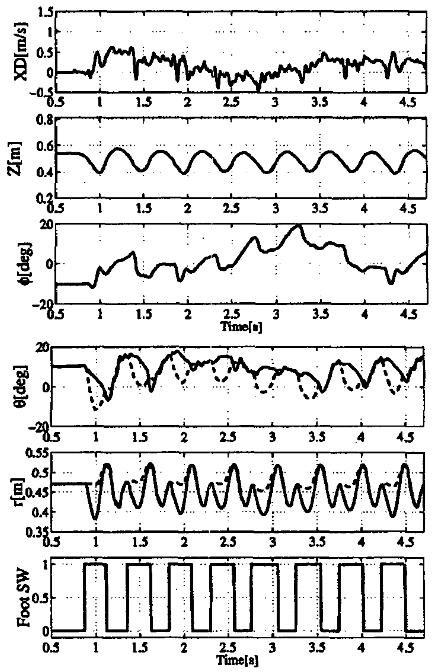

Fig.10 Vertical hopping

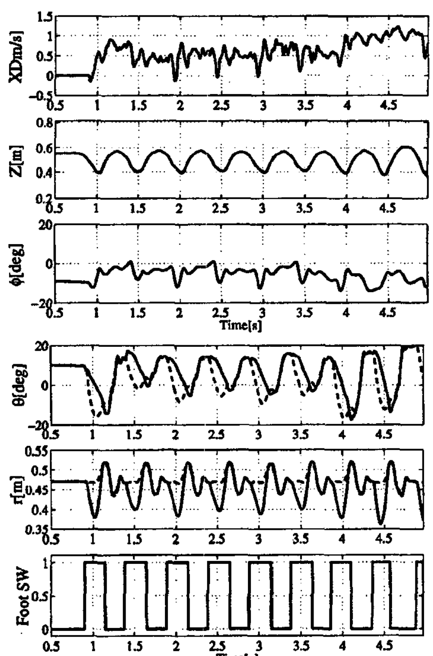

Fig.11 Hopping at 0.5[m/s]

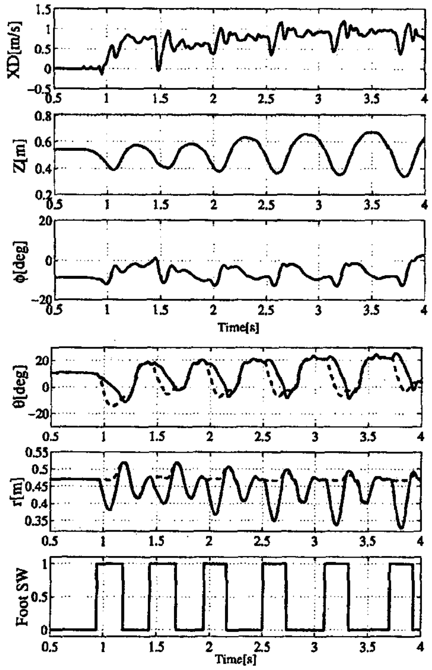

Fig.12 Hopping at 1.0[m/s]

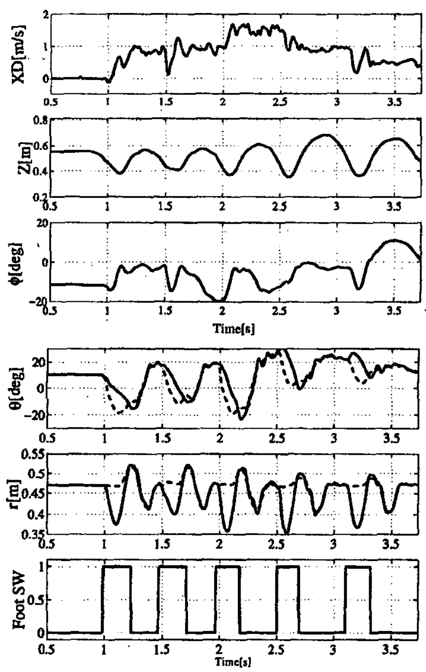

Fig.13 Hopping at 1.5[m/s]